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Planning Transboundary Ecological Risk Assessments at Military Installations

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ABSTRACT

Ecological risk assessments at military installations that are performed to support natural resources management objectives rely on information from the surrounding region. Stressors such as noise, ozone, and ozone precursors cross installation boundaries, and effects of urbanization and highway development are regional in scale. Ecological populations are not limited to one side of the installation boundary. Therefore, a framework for transboundary ecological risk assessment at military installations is under development. This article summarizes the problem formulation stage. Components include: (1) regional management goals such as installation Integrated Natural Resources Management Plans and land acquisition, (2) involvement of multiple stressors, and (3) large-scale assessment endpoint entities. Challenges of selecting measures of exposure include: quantifying exposure to aggregate stressors, describing land cover consistently in the region, describing rates of land-cover transition, scaling local measurements to a region, and aggregating or isolating exposures from within and outside of the installation. Measures of effect that are important to transboundary or regional ecological risk assessments at military installations are those that represent: effects at a distance from the stressor, large-scale effects, effects of habitat change or fragmentation, spatial extrapolations of localized effects, and integrated effects of multiple stressors. These factors are reflected in conceptual models.

Key Words: ecological risk assessment, regional risk assessment, problem formulation, military, scaling.

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INTRODUCTION

Ecological risk assessment frameworks for military training and testing activities have been developed in the past few years, both for general military programs (Suter *et al.* 2002a) and specific activities such as low-altitude aircraft overflights (Efroymson *et al.* 2001a; Efroymson and Suter 2001). These frameworks are elaborations of the U.S. Environmental Protection Agency (USEPA) framework for ecological risk assessment (USEPA 1998). Risk assessment frameworks for military applications provide approaches to assessing risks to animal populations, plant communities, and ecosystem processes within the boundaries of military installations as well as in outlying, affected areas (*e.g.*, below military-controlled airspace). Another military environmental assessment framework provides metrics for assessing the resiliency of generic environmental settings to explosive-residue contamination, based on factors that influence the fate and transport of contaminants (Houston *et al.* 2001). The nature and scale of on-base disturbances associated with training activities are described in Demarais *et al.* (1999), Efroymson *et al.* (in press), and the risk assessment frameworks mentioned earlier. However, the regional scale of many stressors created by installations or by development in surrounding jurisdictions, as well as the regional scale of potentially affected receptors, deserves more emphasis in ecological risk assessment.

Although risk managers have tended to manage risk on a local scale, reasons for examining risks at the regional scale are becoming more evident. Stressors and effects cross the boundaries of military installations. Air pollutants and water pollutants can travel long distances, and compliance with the Clean Air Act and Clean Water Act requires knowledge of the source of the pollutants, even if they are on the opposite side of the military base boundary. Military airspace typically crosses over civilian lands. Vertebrate populations and metapopulations do not observe the boundaries of installations, and management of species under the Endangered Species Act may require habitat management on both sides of the fence. For example, 34 listed (threatened or endangered) and one candidate species on or adjacent to 32 U.S. western, arid military installations are threatened by habitat loss and degradation from various sources of mostly off-base land-use change and other stressors (Table 1, data from Tazik and Martin 2002). Moreover, "the interests of the Army and the RCW [red-cockaded woodpecker, *Picoides borealis*] are best served by encouraging conservation measures in areas off the installation" (Department of the Army 1996). Clusters of the federally endangered RCW that are located off-base but demographically connected to on-base populations are included in counts toward U.S. Army Regional Recovery Goals (Beaty *et al.* 2003).

In a non-military example, grizzly bear, elk, moose, bighorn sheep, bison, and grey wolf in Yellowstone National Park depend on lands outside of park boundaries to support their populations (Kelson and Lilieholm 1999). Similarly, forest bird species richness on agricultural lands is a linear function of the log of the size of adjacent, remnant forest (Freemark and Merriam 1986). Moreover, invasive plants move across institutional boundaries.

ENCROACHMENT

Many of these transboundary issues from the military perspective are encompassed in the term "encroachment." Encroachment is defined by DoD as "the

Table 1. Stressors causing habitat loss for 34 threatened or endangered and 1 delisted species residing on or near western arid military installations (Tazik and Martin 2002).

Stressor	Percentage of species affected[1]
Hydrologic alterations	49
Urban/suburban development	46
Livestock grazing	43
Agricultural development	37
Nonnative species invasions	29
Mining/energy development	17
Timber/woodcutting	9

[1]As Tazik and Martin (2002) note, species can be included in more than one category, so the percentages do not add up to 100%.

cumulative result of any and all outside influences that inhibit normal military training and testing" (GAO 2002, p. 6). The U.S. General Accounting Office (GAO) has identified eight encroachment issues: compliance with endangered species legislation on military installations, application of environmental statutes to unexploded ordnance and munitions, competition for radio frequency spectrum, required consultation with regulators regarding activities potentially affecting protected marine resources, competition for airspace, the application of the Clean Air Act to base-generated air pollution, the application of noise abatement rules to training and testing activities, and urban growth around military installations (GAO 2002). According to the GAO (2002), the impact of encroachment on training ranges has increased over the past several years, and over 40% of installations have reported encroachment issues (USAEC 2003a).

Encroachment related to the Endangered Species Act (ESA) affects various aspects of military training and testing. The example that is most often cited in the popular press is the designation of 10% of Camp Pendleton as critical habitat for several endangered species, which limits the area of beach available for amphibious assaults, off-road vehicle use, the digging of fighting positions, the number of days of weapon systems use, and nighttime helicopter operations (GAO 2002). Similarly, critical habitat designation for the desert tortoise (*Gopherus agassizii*) has hindered Fort Irwin's ability to expand training activities (Tazik and Martin 2002). The military training schedule, approved training area, and fire management of grassland at Fort Huachuca are affected by the distribution of agave cactus species, one of the primary food resources for the lesser long-nosed bat (*Leptonycteris curasoae yerbabuenae* Petryszen) (Tazik and Martin 2002). In another example, the Sonoran pronghorn (*Antilocapra americana sonorienisis*), an endangered subspecies, has hindered training at the Barry M. Goldwater Range in Arizona. High explosive ordnance deliveries have been canceled in 7% of missions and moved in another 26% between 2000 and 2002. Ironically, the animals often prefer the watering holes and young vegetation found in craters of bombing ranges (Tobin 2004).

Urban development encroaches on the military mission, including the management of natural resources at many installations. For example, the frequent understory burns of longleaf pine forests that are required to maintain habitat for RCW have been thought to contribute to the poor air quality of Columbus, GA, the city adjacent to Fort Benning (*Ledger Enquirer* 2000). Furthermore, individuals and populations of rare species are often concentrated in isolated vegetation community remnants on military land. Large areas of undeveloped land on military installations often provide a refuge for rare species that were once abundant, but whose habitat was destroyed or compromised by development of lands surrounding the installation. As a result, military lands support a higher number of rare species per land area than most other federal lands in the United States (Leslie *et al.* 1996). This rarity means that habitat changes on military lands can be associated with high risk to rare species.

The encroachment of environmental regulations leads to at least two situations that may recommend transboundary ecological risk assessments: (1) DoD or regional planners may be interested in attributing the causes of noncompliance to off-base or on-base sources, whichever is appropriate, and (2) DoD may implement mitigation measures such as land swaps or conservation easements to facilitate compliance with environmental statutes. These latter options are part of the Private Lands Initiative (USAEC 2003a) and are authorized in the current National Defense Authorization Act.

REGIONAL RISK ASSESSMENT

Regional-scale ecological risk assessments have been conducted for a variety of purposes. The USEPA's Office of Research and Development has a program on Regional Vulnerability Assessment [(ReVA), USEPA 2004], the goal of which is to develop an approach for comparing near-term and long-term vulnerabilities of regions such as watersheds and multistate areas (Carpenter and Lunetta 2000). A challenge in ReVA is to develop stressor profiles for various stressors that act at the regional scale. In the mid-Atlantic study area, these stressors include: acid deposition, coal mining, human population, landscape pattern, agricultural nitrogen, ozone, pesticide applications, soil redistribution, and ultraviolet B radiation (Carpenter and Lunetta 2000).

In another implementation of regional risk assessment, conceptual models have been developed for use in attributing causes of adverse conditions in South Florida and evaluating restoration options (Gentile *et al.* 2001). The stressors that are the subject of these models include natural events, such as hurricanes, droughts, freezes, fires, sea-level rise, and variability in precipitation, as well as anthropogenic stressors, such as modification of habitats and hydrology, nutrient harvesting, recreation, toxic chemicals, and climate change (Gentile *et al.* 2001).

Other examples of risk models illustrate their versatility and utility. Graham *et al.* (1991) conducted a regional ecological risk assessment for a forest impacted by ozone to demonstrate (1) the importance of using a spatially explicit model, (2) the importance of contingent effects (ozone, followed by bark beetle attacks), and (3) the link between terrestrial and aquatic effects. Relative risk models were used to rank and sum risks from multiple stressors in assessments in Port Valdez, Alaska (Wiegers *et al.* 1998) and a Tasmanian agricultural catchment (Walker *et al.* 2001). A similar risk-ranking model was used to evaluate relative spatial risks associated with land-use change in and near a Brazilian rain forest reserve (Moraes *et al.* 2002).

These models and frameworks for regional risk assessment highlight the importance of regional-scale risk assessments to address questions related to regional-scale stressors, landscape features, hydrology, or nutrient cycles. Landis and Wiegers (1997, p. 289) note that assessment at the regional scale "requires additional consideration of scale, complexity of the structure, and the regional spatial components: sources that release stressors, habitats where the receptors reside, and impacts to the assessment endpoints." The problem formulation stage of assessment becomes increasingly important as the complexity and scale of analysis and number of stakeholders increase.

OBJECTIVE

This study calls attention to the potentially unique features of transboundary ecological risk assessments in the vicinity of military installations that should be considered in the planning stage of assessment, or, in risk assessment jargon, the *problem formulation* stage. Aspects of regional or transboundary risk assessment that are elaborated here, beyond the general guidance that is published elsewhere, include:

- Management goals that are unique to the military or to regional institutions in proximity to military installations,
- The wide range of physical stressors that are present and often controlled at the regional scale,
- The large spatial scale of potential assessment endpoint entities, and factors that increase their susceptibility to particular stressors,
- Indirect effects and exchanges between the installation and region that are represented in the conceptual model,
- Measures of exposure, such as land-cover categories, transition rates between land-cover types, and data interpolation methods, and
- Measures of effect, such as remotely sensed information, habitat suitability models, and monitoring protocols.

In addition, prescriptive aspects of these assessments are described, such as: the need for cooperation and collaboration among institutional entities, the need to integrate risks from multiple stressors, the need for consistency in measures of exposure and effects on both sides of the installation fence, and the potential need to attribute causality to stressors on one side of the fence or the other (or to apportion blame appropriately). In the remaining text we elaborate on typical components of ecological risk assessment frameworks, as described in USEPA (1998) and, more specifically for military activities (Suter *et al.* 2002a), with particular emphasis on aspects of problem formulation. Attention to detail during the problem formulation stage of a risk assessment leads to more rigorous analyses.

IDENTIFICATION OF MANAGEMENT GOALS

The practice of regional ecological risk assessment around military installations is applicable to many scenarios in which land uses change. These may include the development of new training or testing ranges on an installation; the alteration of natural resources management activities, such as prescribed burns; land acquisition by military installations; the development of new highways and other roads in the region; residential development; and commercial and industrial development. Changes in pollutant releases may occur even in areas where land-use categories are not changing, and regional predictions of regulated chemical concentrations are needed to influence calculations of Total Maximum Daily Loads of pollutants that meet water quality standards. Land-use change outside of installations may remove habitat for threatened or endangered species, thus forcing military installation managers to commit more resources to species management. Most scenarios involve prospective applications of risk assessment. Practitioners of transboundary risk assessment at military installations would include resource managers or their agents on both sides of the base boundary.

Management goals for particular installations are set forth in Integrated Natural Resources Management Plans (INRMPs). These plans describe the balance between mission goals and environmental goals, management goals (including recreational land uses) and timeframes, recommended projects (*e.g.*, ecological restoration or wetland protection) and expected costs, environmental legal requirements, and the ecoregional context of the installation's resources. INRMPs are developed with input by the U.S. Fish and Wildlife Service, state wildlife agencies, and the general public, and they are used by installation natural resource managers, planners, and others conducting environmental assessments for proposed agency actions (DoD and USFWS 2002).

On installations, risk assessments could be conducted to support environmental impact statements or other environmental assessments for new training or testing activities, INRMPs, endangered species recovery plans, decisions concerning environmental restoration, or decisions about which lands adjacent to the installation to lease or purchase. McKee and Berrens (2001, p. 125) discuss the economics of habitat acquisition: "to achieve a cost-effective land acquisition program, the Army must know beforehand the quantity and quality of land that it will require to ensure the survival of the species."

The DoD Private Lands Initiative (PLI) involves cooperative agreements between the U.S. Army and nongovernmental organizations to purchase land titles or conservation easements for conservation or training buffer purposes (USAEC 2003a). The National Defense Authorization Acts for Fiscal Year 2003 and Fiscal Year 2004, codified at 10 USC 2684a, authorize the Secretary of Defense or the secretary of a military department to enter into agreements with states, cities, counties, or private entities concerned with conservation of land or natural resources "to address the use or development of real property [*i.e.*, to acquire land or other interest in a property] in the vicinity of a military installation for purposes of (1) limiting any development or use of the property that would be incompatible with the mission of the installation; or (2) preserving habitat on the property in a manner that (a) is compatible with environmental requirements; and (b) may eliminate or relieve current or anticipated environmental restrictions that would or might otherwise interfere, whether directly or indirectly, with current or anticipated military training, testing, or operations on the installation." The U.S. Army refers to this program as the Army Compatible Use Buffer (ACUB). Under this authority Fort Irwin, California, is expanding by 118,000 acres into prime desert tortoise habitat, and the Army is providing $75 million for tortoise conservation (Gerwin 2004). ACUB and related land acquisition efforts would benefit from transboundary ecological risk assessments.

In practice, private, commercial land managers outside of military installations may conduct qualitative risk assessments to ensure that they do not improve habitat for threatened or endangered species, if ESA restrictions would reduce their production [*e.g.*, timber companies with land in North Carolina at risk of RCW habitat designation, Drake and Jones (2002)]. However, the management goals of most large-scale land managers include increasing or at least maintaining the abundance of species of special status.

Retrospective regional risk assessments might also be undertaken if adverse ecological effects are observed, but the responsible stressor or institutional entity is not easily identified. The USEPA's *Stressor Identification Guidance Document* and related papers (Suter *et al.* 2002b; Cormier *et al.* 2003; Norton *et al.* 2003) provide principles for (1) determining causality in aquatic ecosystems and (2) supporting conclusions with evidence that are useful for conducting transboundary or other regional risk assessments. For example, they recommend an evaluation of the association of measurements of exposure and effects, including spatial co-occurrence, spatial gradients, temporal relationships, and temporal gradients, as well as the association of effects with mitigation or manipulation of causes. Retrospective risk assessments may also be undertaken to determine comparative or relative risk associated with stressors acting in different spatial areas (Landis and Wiegers 1997), and prospective or retrospective assessments may evaluate risk from different remedial or restoration actions [*e.g.*, net environmental benefit analysis, Efroymson *et al.* 2004].

Regional or transboundary ecological risk assessments could be undertaken to serve other regional planning purposes. For example, Florida and Georgia have passed legislation defining Developments of Regional Impact (DRI). Development projects of sufficient size (based on published thresholds) to have an impact beyond a local government's jurisdiction are subject to review by adjacent jurisdictions in order to avoid potential conflict. DRI projects in Florida include large residential developments, airports, power plants, and large shopping centers (Kolakowski *et al.* 2000). Nineteen categories of developments in Georgia that are potentially subject to DRI considerations are described in GDCA (2002). Types of impact that are considered under the Florida Environmental Land and Water Management Act of 1972 include environmentally sensitive areas, transportation, capital facilities, emergency services, historical resources, the economy, recreation, energy, education, and housing (Kolakowski *et al.* 2000).

Although military installations are not specifically mentioned in DRI legislation (to our knowledge), they are increasingly being notified about regional developments. For example, the Growth Management Act of Florida was recently amended to require counties and municipalities to notify commanding officers of military installations if the comprehensive zoning plan and land development regulations may affect the "intensity, density or use of land adjacent to the military base." In addition, local governments must alter comprehensive plans by June 2006 to include criteria to improve compatibility of adjacent or proximate lands with military installations (Florida DCA 2004). Transboundary ecological risk assessments may be useful in the context of future regional planning at military installations.

COOPERATION AMONG INSTITUTIONAL ENTITIES

Clearly, the conservation of wide-ranging populations depends on cooperation of institutional entities that own property comprising habitat, as well as regulatory entities and other stakeholders that have an interest in their survival. Regional or transboundary ecological risk assessments depend on the cooperation and collaboration of institutional entities to provide information to support the characterization of exposure and effects, as well as information on future or past ecological management goals. The problem formulation stage of an ecological risk assessment is the appropriate stage for stakeholders to become involved (USEPA 1998).

Cooperation among stakeholders is recommended for conservation, training, and development purposes. INRMPs include procedures for consultation with "all interested groups and individuals that represent an interest in natural resources" (Legacy Resource Management Program 2002, p. 1–4). For example, Ober *et al.* (2000) and Tazik and Martin (2002) note that the conservation of lesser long-nosed bats is dependent on the cooperation of a large number of landowners in the region of Fort Huachuca, because they feed over a large area with patchy locations of forage (agaves, *Agave* L. spp.; yucca, *Yucca* L. spp; and saguaro, *Carnegia gigantea*). In its *Management Guidelines for the Red-Cockaded Woodpecker on Army Installations*, the Department of the Army (1996) recommends that if RCW nesting areas are located on installation lands and foraging areas are located offsite (or *vice versa*), the U.S. Fish and Wildlife Service (FWS) and installations "should initiate cooperative management with these landowners, if such efforts would compliment [sic] installation RCW conservation initiatives." Moreover, the FWS and installations should participate in promoting cooperative RCW conservation plans, solutions, and efforts with other federal, state, and private landowners in the surrounding area" (Department of the Army 1996).

Similarly, land acquisition and other conservation programs (and any future risk assessments associated with them) demand cooperation among stakeholders. For example, the North Carolina Sandhills Conservation Partnership, including the US Army, the North Carolina Chapter of The Nature Conservancy, the North Carolina Department of Transportation, the North Carolina Wildlife Resources Commission, the Sandhills Area Land Trust, the Sandhills Ecological Institute, and the U.S. Fish and Wildlife Service have jointly acquired and manage land and conservation easements around Fort Bragg, North Carolina, to preserve the longleaf pine–wiregrass ecosystem and RCW. This arrangement permits use of additional areas on Fort Bragg for training and increases public recreation opportunities (USAEC 2003b; Dale *et al.* in press).

DEFINITION OF STRESSORS

Stressors are defined in the problem formulation stage of an ecological risk assessment. Stressors that cross military–civilian boundaries (or whose impacts cross these boundaries) and the activities that produce these stressors are listed in Table 2. Many of the listed activities occur on both sides of the installation boundary, but most are predominantly found on one side or the other. For example, explosions occur on military lands, and most urban expansions occur beyond the boundaries of installations, but in both cases, ecological impacts may cross installation boundaries.

Table 2. Stressors that cross military–civilian boundaries or that impact land areas across the border.

Activity	Stressor	Military	Civilian
Urban development	Loss and fragmentation of critical habitat, alteration of hydrology, alteration of nutrients, heat, light, nonnative vegetation, alteration of habitat structure (buildings, pavement)	X	X
Road development	Noise, loss of habitat, altered hydrology, visual stressor	X	X
Logging	Loss and fragmentation of habitat	X	X
Agriculture	Nutrients		X
Prescribed burns	Loss and fragmentation of habitat, air pollutants	X	X
Wildfires	Loss and fragmentation of habitat, air pollutants	X	X
Troop training	Changes in vegetation from trampling, particulates in air, sedimentation	X	
Tracked vehicle movement	Soil erosion, sedimentation, altered hydrology, noise	X	
Aircraft overflight (training or testing)	Noise, visual stressor, air movement from takeoff/landing	X	X
Release of smokes, obscurants	Metals, chlorinated hydrocarbons, oils	X	
Explosions	Noise, erosion	X	

Tracked and wheeled vehicle movement, explosions, troop movements, and road construction can erode soil, leading to sedimentation in streams. Nitrogen runoff is high on agricultural lands and lower on most installations, so the net transport would be expected to move onto installation lands if topography permits these flows. Emissions of volatile organic compounds (VOCs) and oxides of nitrogen (NOx) from both military installations and the surrounding regions mix in the atmosphere and undergo photochemical transformations to form ozone. Similar sources and chemical processes can also lead to increased concentrations of airborne particulate matter. Smokes and obscurants may be comprised of metals, chlorinated hydrocarbons, or oils in various formulations and may be used as munitions (*i.e.*, grenades or projectiles) or produced from stationary generators. Stressors include the smoke material and its breakdown products (Sample *et al.* 1997). Noise from aircraft overflights, explosions, or highways may cross installation boundaries. The visual stressors associated with aircraft overflights can also be significant for some wildlife such as raptors (Efroymson and Suter 2001). Wildlife populations that cross installation boundaries may be impacted by local events such as road kills (Forman *et al.* 2003). New training ranges, roads, or other development may fragment habitat for particular species. Many of these stressors (urban encroachment, industrial and commercial development, air pollution, and roads) have also been listed as primary threats to national parks (Kelson and Lilieholm 1999).

Urbanization, which exceeds the national average rate near 80% of installations in the United States (GAO 2002), is a stressor that directly affects species habitat and populations [*e.g.*, decreases in grassland nesting songbird density (Haire *et al.* 2000) and decreases in avian diversity and increases in avian biomass (Crooks *et al.* 2004)]. Urbanization alters hydrology and nutrient mass balance, especially at the boundaries of urban areas that consist of edges of paved areas. For the purpose of risk assessment, urbanization must often be decomposed into component stressors, such as paved surface, urban runoff, noise, heat, or nighttime light. These component stressors are most often the exposure parameters in exposure–response relationships.

The challenge of attributing sources of ozone to either side of the installation fence may be illustrated by a description of the chemistry of ozone. Low concentrations of ground-level ozone exist naturally in the atmosphere; however, concentrations may increase as a result of a series of complex photochemical reactions involving VOCs and NOx. Anthropogenic sources of VOCs include most civilian and military activities and processes that involve fuels, paints, and solvents. Biogenic sources of VOCs include trees, crops, and other types of vegetation on both sides of the installation fence. Where these latter sources are abundant, biogenic VOC emissions can sometimes eclipse anthropogenic VOC emissions. All significant sources of NOx involve combustion. These include, for example, burning of fuels for transportation, generating electricity, industrial processes, and construction equipment. Biomass burning from prescribed and wild fires on military installations and in surrounding areas can also generate significant emissions of NOx. Emissions of VOCs and NOx from both military bases and the surrounding regions are readily mixed in the atmosphere and undergo photochemical transformations to form ozone. Clearly, the sources of ozone and its precursors in particular locations are sometimes difficult to identify.

SELECTION OF ASSESSMENT ENDPOINTS

Assessment endpoints are defined as ecological entities (populations, communities, or ecosystem processes), properties (*e.g.*, production, abundance), and levels of effect that are deemed important. Criteria for the selection of assessment endpoints are described in Suter *et al.* (2000) and include policy goals and societal values, ecological relevance, susceptibility, appropriate scale, operational definability, and practical considerations. Regarding scale, assessment endpoint entities for transboundary ecological risk assessments would include vegetation communities (Table 3), wide-ranging populations such as birds that cross installation boundaries, as well as more localized populations that are potentially impacted by stressors that cross installation boundaries.

For example, the endangered RCW flies across installation boundaries in many locations in the southeastern United States. Four of the ten largest RCW populations (*i.e.*, clusters of cavity trees) are on military installations (Fort Bragg, NC; Fort Benning, GA; Fort Stewart, GA; and Eglin Air Force Base, FL), and several other military installations (*e.g.*, Fort Gordon, GA; Fort Polk, LA; Fort Jackson, SC; Camp LeJeune, NC; Peason Ridge, LA; and Military Ocean Terminal Sunny Point) also contain woodpecker clusters (James 1995; Beaty *et al.* 2003). The clusters present on most installations do not constitute viable populations. Therefore, management

Table 3. Dominant vegetation communities of Army, Marine, and Army National Guard Lands (data from Demarais *et al.* 1999).

Vegetation community	Percentage of military land
Southern desert scrub	25.5
Boreal forest	13.2
Northern desert	12.4
Southeast evergreen forest	11.8
Montane woodland brush	10.7
Eastern deciduous forest	10.4
Grasslands	5.0
Northern hardwood-conifer forest	4.5
Pinyon-juniper-oak woodland	2.5
Chaparral-oak woodlands	1.3
Oak savanna	1.3
Pacific rainforest	0.9
Mesquite grasslands	0.3
Tropical vegetation	0.2

efforts would benefit from the modeling of woodpecker populations within a risk assessment context on combinations of military, other public, and private lands. Since 1996 Fort Benning, Fort Bragg, and Fort Stewart have moved more than 110 RCWs to other federal, state, and private forests to help stabilize very small populations (Beaty *et al.* 2003). U.S. Fish and Wildlife Service has prepared a recovery plan for the RCW that proposes regional, population-level, and cluster-level criteria for delisting the species that include regional population sizes, numbers of populations that should include particular numbers of clusters, and plans for habitat management and population monitoring (USFWS 2003).

Similarly, the only population of Sonoran pronghorn, an endangered subspecies, ranges across southwestern Arizona and Mexico. At the end of 2000 about 40% of the home range of the 99 Sonoran pronghorns in the United States was on the Barry M. Goldwater Range, a bombing and gunnery range, with the rest in the Cabeza Prieta National Wildlife Refuge and Organ Pipe Cactus National Monument (Krausman and Harris 2002). This subspecies is of the appropriate scale for regional assessment, is valued by society, and is potentially susceptible to ordnance delivery, aircraft overflights, and collisions with ground vehicles (Krausman and Harris 2002).

Ecological properties of potential wildlife assessment endpoint entities that increase susceptibility to military and nonmilitary stressors are summarized in Table 4. Of these, properties that increase susceptibility to the noise or visual stressors of aircraft overflights were previously described in Efroymson and Suter (2001). Based on these criteria, generic assessment endpoint entities for training or testing activities involving aircraft overflights may include groups of animals such as raptors, waterfowl, amphibians, ungulates, small mammals, cetaceans, and pinnipeds. The desert tortoise, for example, is especially sensitive to habitat loss and fragmentation caused by highways, utility rights-of-way, off-road vehicle use, construction activities, and cattle grazing (Tazik and Martin 2002). In addition, vegetation communities are

Table 4. Examples of assessment endpoint properties that increase susceptibility of terrestrial vertebrates to stressors. Properties lead to either increased sensitivity (s) or increased exposure (e).

Stressor	Endpoint property
Noise	• lack of previous exposure to the sound (s) • high predisposition to auditory damage (s) • reliance on auditory cues to locate young, to locate a mate, to avoid predators, to emerge from hibernation, or to detect prey (s) • seasonal tendency toward energy limitation (s) • sensitivity to sound while raising young (s) • flocking or herding behavior (s)
Habitat loss or fragmentation	• territoriality (s) • dispersal and foraging at scale of fragmentation (e) • edge sensitivity (s) • social breeding (*e.g.*, lekking behavior) (s) • habitat specificity (s) • seasonal tendency toward energy limitation (s)
Air pollutants	• low threshold for toxic effects from ozone, particulates, metals, chlorinated hydrocarbons, oils, *etc.* (s) • high rate of metabolism (e)
Erosion	• requirement for high vegetation cover (s) • (also, see entries under habitat loss or fragmentation)

susceptible to erosion, air pollution, and changes in hydrology. Aquatic communities are susceptible to sedimentation from soil disturbance that may be associated with tracked vehicle movement and troop training.

DEVELOPMENT OF CONCEPTUAL MODEL

Conceptual models are developed during the problem formulation stage of a risk assessment to represent the relationships between sources of chemicals or physical stressors and effects (Suter *et al.* 2000). Most conceptual models for ecological risk assessments of contaminants represent processes of fate and transport (including biological uptake), as well as toxicity to assessment endpoint entities. An example of a published conceptual model for effects of smokes and obscurants on RCW on a military installation is presented in Figure 1.

As Suter (1999a) notes, conceptual models for multiple activities involving chemical and physical stressors can be challenging because of the level of detail that is required to illustrate all connections to assessment endpoints, including indirect effects. Indeed, regional risk assessments tend to emphasize indirect effects on populations, for example, habitat alterations rather than direct mortality and chemical toxicity (although regional-scale air and water pollutants can have regional toxicity). Transboundary ecological risk assessments at military installations need to have

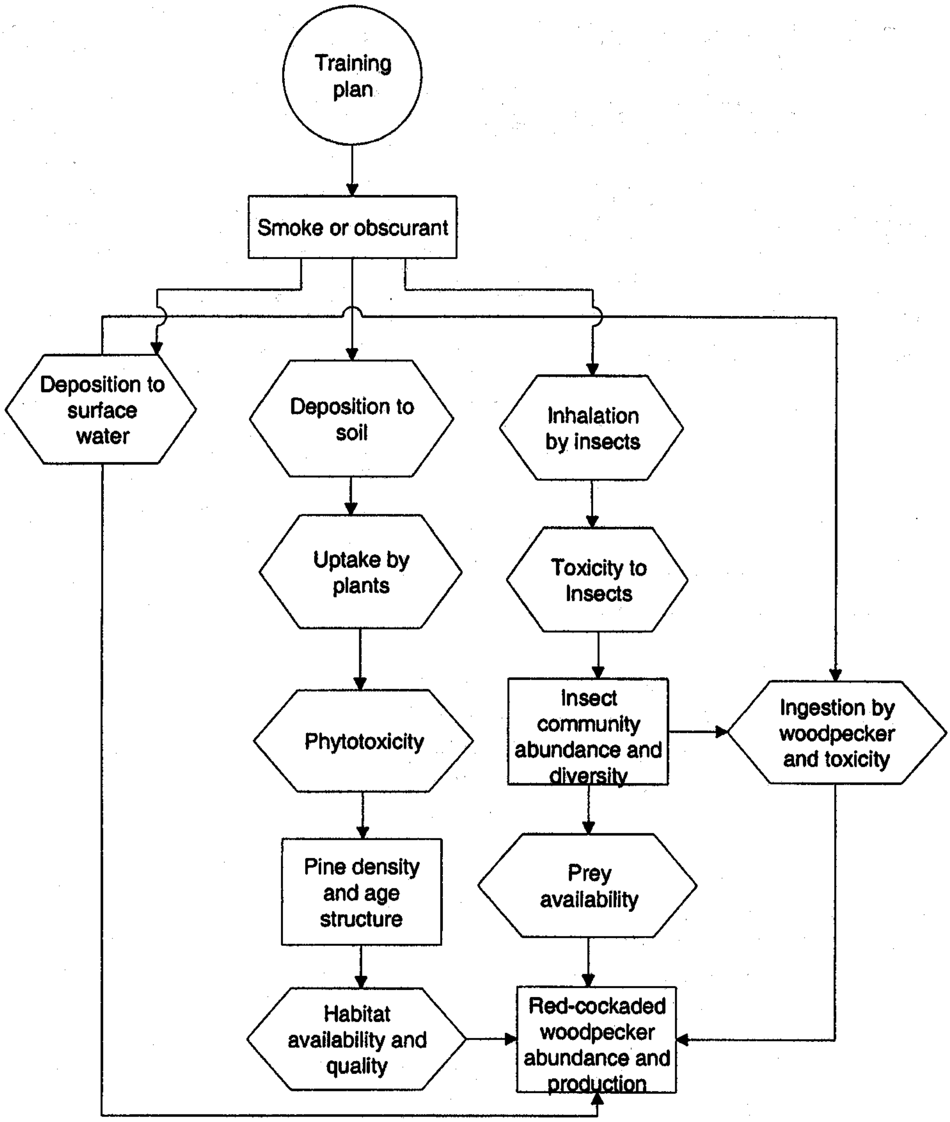

Figure 1. Conceptual model for effect of smoke or obscurant on red-cockaded woodpecker, modified from Sample *et al.* (1997). Rectangles are states, hexagons are processes, and circles are management plans.

conceptual models that reflect spatial locations of stressors and receptors because of the multiple land-management institutions involved. Limburg *et al.* (2002) provide references to support the assertion that "there will be tighter coupling among processes and components with similar rates and overlapping spatial scales." Our conceptual model in Figure 2 distinguishes between on-base and off-base stressors, although the linkages and processes are expressed in more detail on the installation side of the graphic. In this particular example, the RCW population on an

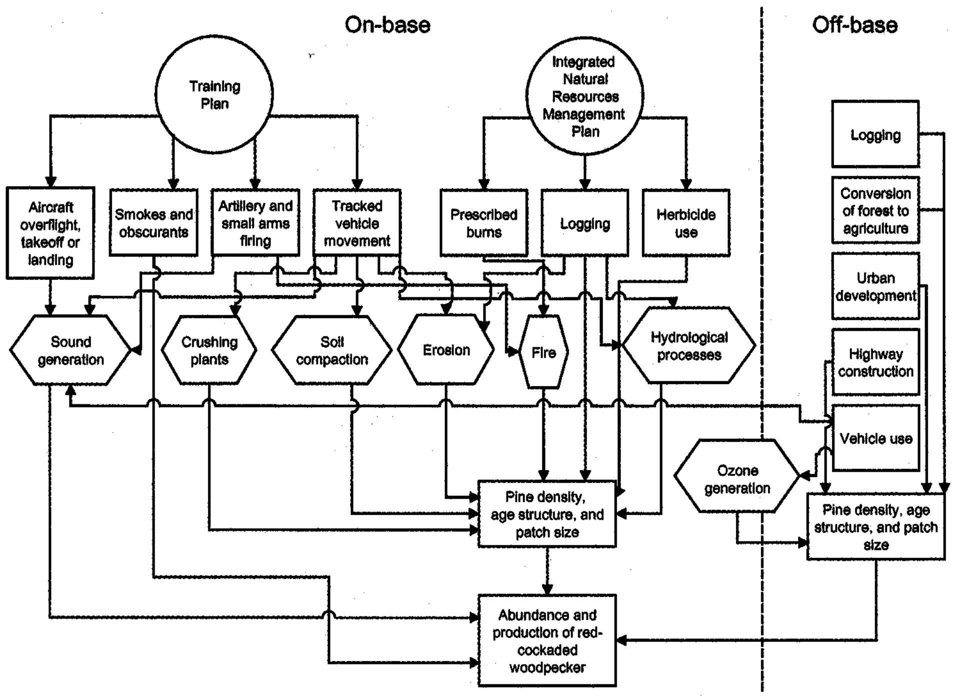

Figure 2. Conceptual model for effects of on-base and off-base stressors on a population of red-cockaded woodpecker at a military installation in the southeastern United States Rectangles are states, hexagons are processes, and circles are management plans.

installation is the assessment endpoint entity of concern, but the model could just as easily have depicted exposure pathways for the regional metapopulation.

Additional modular models could be constructed in a hierarchical manner (as described in Suter 1999b and Suter *et al.* 2002a) to investigate all of the exposure pathways resulting from the off-base activities of logging, highway construction, vehicle movement, urban development, and conversion to agricultural production. Suter (1999b) recommends three types of conceptual models for use in complex risk assessments: activity-specific models (*e.g.*, for a proposed range or development), site models (*e.g.*, hydrologic models, food web models), and receptor models (*i.e.*, for a particular assessment endpoint). In the problem formulation (and therefore the conceptual models) of a regional risk assessment, it is important to note all connections between stressors, for example, whether similar stressors are produced by multiple activities (*e.g.*, noise), whether stressors overlap in space and time, whether effects are additive, and whether exposures are additive (*e.g.*, habitat loss from multiple sources) (Suter 1999b).

DEVELOPMENT OF ANALYSIS PLAN

The analysis plan is the final stage of the problem formulation in which hypotheses related to exposure and effects are evaluated to identify data and models that are required for analysis (USEPA 1998). Key components of the analysis plan are measures of exposure and measures of effects.

Measures of Exposure

Measures of exposure are described in the problem formulation. These measures may include chemical concentrations, area of compacted soil, size and distribution of habitat patches, noise contours, lengths of roads, and so on. Particular challenges that are associated with exposure metrics for regional or transboundary risk assessments at military installations include:

- Quantifying exposure to aggregate stressors, such as "urbanization," in a way that is predictive of effects,
- Describing land cover in sufficient and consistent detail on and off the installation to delimit wildlife habitat,
- Describing rates of land-cover transition accurately,
- Identifying boundaries, sizes, and numbers of patches of similar land-cover or habitat types,
- Scaling point or local measurements to a region (or scaling regional measurements to particular locations), and
- Summing or disaggregating exposures from within and outside of the installation.

Although urbanization and road development are significant stressors that encroach on military missions, including conservation, these stressors may have to be disaggregated into component stressors for exposure-response relationships to be meaningful. Urbanization consists of changes in paved area, vegetation cover, wildlife habitat, soil nutrients, water quality, air quality, structures (physical and visual stressor), noise, nighttime light, heat, vehicle movement, and so on. Exposure-response relationships are available for many of these stressors, but few are available for urbanization, in general. For example, a broad study of avian assemblages along a gradient of urbanization was designed to investigate the role of habitat fragmentation rather than other aspects of urbanization (Crooks 2004). Similarly, Johnson and Collinge (2004) studied the effect of urbanization, as measured by percent of landscape area occupied by anthropogenic features, on numbers of burrow entrances of black-tailed prairie dogs (*Cynomys ludovicianus*) in the Colorado Front Range. Component stressors associated with roads are a subset of those associated with urbanization, and many studies of the impacts of roads cannot attribute causation to particular variables. An exception is a study of the effects of automobile traffic on breeding bird densities, which empirically separated noise from the visual stressor of automobiles and examined literature to determine the relevance of roadkills and pollution to species abundance (Reijnen *et al.* 1995).

Many military installations support a variety of land-cover classes and include their attributes in geographic information systems that are available for use in risk assessments. However, it is rare that data at a comparable level of detail are available for private and public lands in the surrounding region. For example, at Fort Benning, Georgia, more than 40 classes of forest stand data are available, with attributes including many features that are variables in wildlife habitat models, for example, date of planting, area of stand, radial growth within five years, radial growth within ten years, hardwood basal area within stand, pine basal area in forest stand, site index, stand condition, number of stems per acre in stand, and number of longleaf pine stems per acre (SEMP 2004).

In contrast, the most detailed land-cover data for the five counties of Georgia surrounding Fort Benning, obtained from the University of Georgia's Natural Resources Spatial Analysis Lab (part of the Georgia Gap Analysis Program), include just over 20 tree classes (based on 30-m Landsat TM remotely sensed data) without any detailed temporal or spatial attributes. It is also notable that Fort Benning crosses two states, and the land-cover data in Alabama are far less detailed than those in Georgia (USGS 2004a). [Land-cover data from the Alabama Gap Analysis Program are incomplete (USGS 2004b).]

Spatially explicit transition models use rules to specify change in land-cover types for a particular situation (*e.g.*, Debussche *et al.* 1977; Turner 1988; Dale *et al.* 2002). The maps produced from these models can illustrate how changes might occur over time. For example, a map produced from a transition model for Fort McCoy depicts patches of wild lupine (*Lupinus perennis*), which is the obligate host for the larvae of the federally endangered Karner blue butterfly (*Lycaecides melissa samuelis*), at risk of change with tracked and wheeled vehicle training in maneuver areas (Dale *et al.* 2002). When applied to military lands, these models can be used to inform exposure assessment.

The Regional Simulator model (RSim) for use in environmental assessments in the region of military installations is being designed to simulate land-cover changes caused by urban development, road development, and changes in military training activities, as well as resulting ecological risks (Dale *et al.* in press). In this model, rules have been developed to describe transitions to low-intensity and high-intensity urban land-cover classes, and highway development and new military ranges are digitized based on construction plans. In addition, the model will be able to identify patches of contiguous land with identical land-cover or habitat suitability designations, using a modification of the Hoshen-Kopelman algorithm (Berry *et al.* 1994; Constantin *et al.* 1997). This computationally intensive algorithm gives a unique label to each spatially discontinuous habitat patch. Alternative rules for defining adjacency, such as whether or not diagonally adjacent cells of the same land-cover designation are in the same patch or whether cells a certain distance apart should be considered to be within the same patch, may influence the outcome of patch-finding algorithms. Exposure metrics such as patch area (Carlsen *et al.* 2004) and number of territories (Walters *et al.* 2002) are related to demographic profiles, abundances, and extinction probabilities of various species of wildlife.

The spatial and temporal scales of the analysis of exposure are the scales at which the exposure-response model is most relevant. Limburg *et al.* (2002) define the scale of an ecological property as the scale at which the property has "greatest coherence." Few measurements of environmental stressors are from monitoring networks that were designed with the regional scale in mind. As Andelman and Willig (2004) note, most ecological measurements are performed at spatial scales of 10 m^2 or less and durations of five years or less. Often, the regional assessor must make due with measurements at point locations and methods to interpolate between points (and sometimes extrapolate) to larger regions. Spatial interpolation is a challenge if the land-cover categorization varies within the region, for example, if installation and off-installation land-cover categorizations are different. Even within a land-cover category, various spatial interpolation methods of exposure are only appropriate if certain assumptions are met; Woodbury (2003) discusses Thiessen polygons and kriging in this context.

Air quality monitors and networks of air quality monitors are deployed by state and federal regulatory agencies to determine compliance with National Ambient Air Quality Standards. They are designed, sited, and operated to take air quality samples that are representative of a large area. Thus, they are suited to regional risk assessments if the region roughly coincides with the area represented by one or more monitors. Air quality monitors are poorly suited, however, for characterizing local air quality and its effects (except at the location of a monitor). As such, there is some question as to whether these air quality monitors provide effective air pollutant exposure metrics of individual human health or local vegetation growth and survival. Another concern about these monitoring stations is that although they are fairly representative of a large area in the layer of the atmosphere near the land's surface, they do not capture the variability in pollutant concentrations with altitude. This omission makes it difficult for atmospheric scientists to understand how pollutants and pollutant precursors mix and are transported.

Finally, the issue of aggregation of exposure may be illustrated with reference to noise. Exposures to noise may be measured or modeled. Modeled exposures to noise can be added only if the noise exposures have similar frequency and temporal characteristics. For example, Wasmer Consulting (2003) provides instructions for adding noise from contours independently calculated for military and civilian aircraft in the same region. However, methods are not available to integrate wildlife exposures to sources of various types of sound in a region. That is, the decibel results from models used to estimate impulsive blast noise exposures [*e.g.*, BNOISE2 (ERDC 2004, USACHPPM 2004)] cannot be added to the decibel results from models used to estimate continuous sound, such as NOISEMAP (AFCEE 2004), which is used to model overflight sound. Frequency differences in the sounds would need to be determined before a true noise addition could occur (Efroymson *et al.* 2001b). Also, peak sound levels are probably more closely related to ecological effects than the day-night or annual average sound levels that are typically produced from these models, but peak sound levels are usually modeled based on one source. Many sources of sound in the regions of military installations (highway noise; tank noise, especially loud during small radius turns) are rarely modeled.

Measures of Effects

Measures of effects are "statistical or arithmetic summaries of observations used to estimate the effects of exposure on the assessment endpoint" (Suter *et al.* 2000). Examples of measures of effect are: (1) a sound pressure level that results in a bird flushing from its nest, (2) the proportion of habitat lost that leads to the extinction of a population, (3) the minimum number of reproducing pairs needed to sustain a population, or (4) SUM06, a summary statistic for ozone effects on vegetation, calculated as the sum of all hourly values greater than 0.06 ppm (ppm-hrs) (USEPA 1996). These measures are developed as part of the problem formulation for an ecological risk assessment. Measures of effect that are uniquely important to transboundary or regional ecological risk assessments at military installations are those that represent: effects at a distance from the stressor or source of the stressor, large-scale effects, indirect effects such as from habitat change or fragmentation, spatial extrapolations of localized effects, and integrated effects of multiple stressors.

For example, effects of noise and visual stressors from aircraft overflights and vehicles on roads can occur at a distance from their sources. Thresholds and other ecological response models for noise and visual stressors of aircraft overflights are available in Efroymson and Suter (2001), and estimates of road-effect zones are provided by Forman and Deblinger (2000). Similarly, ozone and other air pollutants act at a distance from their sources.

Measures of large-scale effects can be computed with data available since the 1970s from satellites and even earlier from some other remote sensing platforms. Underwood *et al.* (2003) developed hyperspectral techniques for monitoring iceplant (*Carpobrotus edulis*) and jubata grass (*Cortaderia jubata*), two invasive species in the coastal zone of Vandenberg Air Force Base in California. Moreover, Leyva *et al.* (2002) have used Light Detection and Ranging (LIDAR) data to map the vertical distribution of vegetation supporting black-capped vireo (*Vireo atricapillus*) at Fort Hood, Texas. Washington-Allen *et al.* (in press) used the Soil-Adjusted Vegetation Index derived from historical Landsat imagery to assess the effects of military training and testing activities and drought on vegetation at National Guard Camp W. G. Williams in Utah from 1972 to 1997. All of these applications could be regional in scope, and data from these remote-sensing technologies are not limited to military installations.

As with exposure, spatial extrapolation or aggregation of effects is a challenge. Rastetter *et al.* (1992) caution ecological assessors about aggregation errors that can arise when fine-scale equations are used to predict coarse-scale behavior. For example, Woodbury *et al.* (2002) examined the sensitivity of tree basal area predictions by the ECLPPS ozone-tree model to the choice of cell size. This vegetation property varied with cell size because of an aggregation error in the algorithm used to calculate shading.

Habitat models can be considered measures of exposure (of individual animals or populations to disturbance) or measures of effects (on species-specific habitat). Habitat suitability indices are estimates of carrying capacity (USFWS 1981), and other habitat suitability models can be used to estimate the presence or absence of a given species. Based on available land-cover data, habitat models for use on-base and off-base would probably require different parameters, which means that uncertainty might be much larger in poorly studied regions outside of military installations than within installations with strong conservation programs. Habitat models may not be necessary for the estimation of current species locations on-base, where locations for threatened, endangered, and other valued species are periodically surveyed. For example, dynamic models of vegetation growth can provide much of the vegetation growth data that are available on Fort Benning for outlying areas, but these models are highly dependent on management assumptions. Yet models can greatly reduce field efforts [*e.g.*, identification of threatened calcareous habitat at Fort Knox Military Preserve (Mann *et al.* 1999)]. Models can also identify habitats on sites that may not be accessible because of unexploded ordnance [*e.g.*, potential locations at Fort McCoy of wild lupine (Dale *et al.* 2000)].

Simulation models may incorporate thresholds and other measures of effects for use in ecological risk assessments. As stated earlier, RSim is designed to simulate (1) land-cover changes caused by urban development, road development, and changes in military training activities; (2) resulting changes in air quality, water quality, soil nutrients, and noise; and (3) changes in vertebrate populations and their habitats (Dale *et al.* in press). The model will include thresholds for ecological effects and continuous exposure–response relationships. Examples of effects that will be estimated and mapped for the Fort Benning, Georgia, case study include RCW clusters where woodpeckers may temporarily flush from nests because of noise, gopher tortoise (*Gopherus polyphemus*) burrows where animals are potentially immobilized because of blast noise, areas around roads that are likely to have low abundances of particular songbirds, and vegetation predicted to have at least a 20% reduced yield due to ozone exposure.

CONCLUSIONS

Many of the natural resources management goals of military installations and other lands in the region involve physical and chemical stressors and ecological populations that move across installation boundaries. Risk assessments at military installations should be conducted at the regional spatial scale if the management goals are regional. Components of the problem formulation stage of a transboundary risk assessment framework include (1) regional management goals such as developing installation Integrated Natural Resources Management Plans and acquiring land for conservation purposes, (2) identification of multiple stressors, (3) selection of assessment endpoint entities that are appropriate for a large spatial scale, and (4) description of linkages between stressors and assessment endpoint entities in conceptual models. The characterization of exposure of a transboundary risk assessment will have the following challenges: quantifying exposure to aggregate stressors such as urbanization, describing land cover and rates of land-cover transition in sufficient detail and consistently across the assessment region, scaling point or local measurements to a region, and aggregating or isolating exposures from within the installation and in surrounding areas. The characterization of effects for a transboundary or regional ecological risk assessment at a military installation may include: thresholds for noise or distance from aircraft overflights, road-effect distances, species monitoring methodologies such as remote sensing, and habitat models. If transboundary ecological risk assessments are well planned, then the results will have a high likelihood of supporting natural resources management goals for military planners, highway developers, county and urban developers, and other interested parties.

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